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**FINAL REPORT FOR AFOSR  
GRANT F49620-94-1-0232**

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Co-principal investigator:

John H. Vande Vate

Institution:

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Atlanta, GA 30332-0205

Grant Number:

F49620-94-1-0232

## **2. Objectives**

We have broadened our objectives to include exploration of "self-organizing logistics systems". This was an opportunistic decision to exploit some immediately applicable ideas that emerged tangentially from the current project.

## **3. Status of effort**

We have recently diverted some effort to the exploration of self-organizing logistics systems within warehouses. We have visited several high-volume warehouses to understand better the problems of order-picking; and we have tested our ideas at one commercial warehouse. We have not, however, finished the mathematical analysis, which appears to be quite difficult as it requires mathematics from the emerging field of dynamical systems.

Meanwhile, we continue to collaborate with Pratt & Whitney to develop a computer system that will use information about part geometry and mass distribution to predict the engine vibration from a given assembly and will recommend a "good" assembly that produces little vibration. This effort is aimed at reducing vibration in the engine of the F-22.

We continue to develop software tools for modelling the shape and mass distribution of the engine resulting from a given assembly and optimization tools for finding an assembly that minimizes various approximations of the vibration.

We hope to get data soon from Pratt & Whitney so that we can begin to evaluate the performance of our tools on real engines. We have scheduled a visit to the Pratt & Whitney site at which turbine blades are manufactured.

## **4. Accomplishments/New findings**

Our main accomplishment has been to devise and analyze a class of heuristic algorithms that guide assembly of jet engine rotors to reduce static unbalance. All perform several orders of magnitude faster than the algorithms used in current practice. Moreover, unlike current practice, our algorithms come with guarantees on the quality of the resulting balance. In fact, when the number of blades is even, but not a multiple of four, our heuristic provides the strongest possible worst case performance guarantee. In other

words, no other procedure can provide a better performance guarantee---not even the hopelessly impractical procedure of trying all possible ways of sequencing the blades.

The performance guarantee of our procedure is expressed in terms of the magnitude of the difference between successive weights of fans. This kind of bound allows us to set the manufacturing tolerances for the blades at exactly the level required to guarantee a specified quality of balance in the final assembly. For example, the sixth stage turbine disc of the Pratt & Whitney PW 2000 jet engine must be statically balanced at a minimum of 900 rpm to within 1.0 ounce-inch without adding counterweights. Our procedure guarantees this quality of balance if the difference between successive weights is no more than 0.08 ounces. To provide the same guarantee when the blades are sequenced according to current practice, the difference between successive weights must not exceed 0.008 ounces, a manufacturing tolerance that is an order of magnitude more demanding. Thus, intelligent assembly allows the manufacturing tolerances to be relaxed significantly while guaranteeing the same performance specifications.

This illustrates the theme of our research: Intelligent assembly can reduce manufacturing costs without sacrificing performance.

Our work produced an interesting insight that may have practical implications: Our procedure has a better guarantee of performance when the turbine disc has an even number of blades---but not a multiple of four. Intuition supports this, at least in retrospect: When there are an even number of blades, we can place opposing pairs so that the resultant unbalances counteract each other...except when the number of blades is a multiple of four, when orthogonal pairs are independent of one another. Of course this effect is less pronounced with more blades; but it suggests that, where possible, turbine discs should be designed to have an even number of blades but not a multiple of four. Such discs will be easier to balance.

On the topic of self-organizing logistics systems, we have discovered a way to coordinate order-picking in a warehouse so that a balance of work among the pickers spontaneously emerges.

## 5. Personnel supported

John J. Bartholdi, III  
John H. Vande Vate  
Vijay Nori

professor  
associate professor  
graduate student

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## **6. Publications**

### **6.1 Submitted but not yet accepted:**

S. V. Amiouny, J. J. Bartholdi, III and J. H. Vande Vate. "Heuristics for balancing turbine fans", submitted to Operations Research (1995).

J. J. Bartholdi, III, D. D. Eisenstein, C. Jacobs-Blecha, and H. D. Ratliff. "Design of 'bucket brigade' production lines", submitted to Operations Research (1995).

S. Chang, D. Llewellyn, and J. H. Vande Vate. "Two-lattice polyhedra: duality", submitted to Mathematics of Operations Research (1995).

S. Chang, D. Llewellyn, and J. H. Vande Vate. "Two-lattice polyhedra: extreme points", submitted to Mathematics of Operations Research (1995).

S. Chang, D. Llewellyn, and J. H. Vande Vate. "Two-lattice polyhedra: finding a maximum vector", submitted to Mathematics of Operations Research (1995).

### **6.2 Accepted but not yet published:**

J. J. Bartholdi, III, L. A. Bunimovich, and D. D. Eisenstein. "Dynamics of 2- and 3-worker 'bucket brigade' production lines", to appear in Operations Research (1995).

J. J. Bartholdi, III and D. D. Eisenstein. "A production line that balances itself", to appear in Operations Research (1995).

A. Ramudhin, J. J. Bartholdi, III, J. M. Calvin, J. H. Vande Vate, G. Weiss. "A probabilistic analysis of 2-machine flowshops", to appear in Operations Research (1995).

### **6.3 Published**

(None)

## **7. Interactions/Transitions**

### **A. Participation/presentations at meetings**

"Production lines that balance themselves", presented by J. Bartholdi at The Wharton School, University of Pennsylvania, March 1995

### **B. Consultative and advisory functions to other agencies**

Pratt & Whitney, Middletown, Connecticut. We have talked frequently on the phone and exchanged e-mail discussing how our procedures for balancing turbine fans could be incorporated most easily into the production process. We have also had continuing discussions on what engine data would best support computations to improve dynamic balance of jet engines. Our contact has been William A. Weiblen, Manager of Assembly Technical Support.

Delta Airlines, Technical Operations Center, Atlanta, GA: Visit of May 31, 1995 by J. Bartholdi and V. Nori and subsequent frequent phone calls and e-mail exchanges. Delta representative: Michael Wilson, Power Plant Engineer. We toured Delta's rebuild facilities, where they renovate jet engines of several types. We discussed how our heuristics for balancing turbine fans can help them achieve better balanced engines; we also began exploring how the balance procedure affects inventory strategies and how the procedure should account for this.

Delta Airlines, Flight Operations, Atlanta, GA: Visits of November 9, 1994 and January 30, 1995 and subsequent phone calls. Delta representative: John A. Tocher, OASIS program manager. We are studying the loading of aircraft and advising in the design of a software system to plan loads.

### **C. Transitions**

I advised Environmental Research Systems Inc. about the use of spacefilling curves to index a geographical database. This has been implemented by them in their flagship GIS product, ARC/INFO: The ARC/PLOT language now includes the command "spatialorder(<network>)", the documentation of which cites my work. This has also been incorporated in other commercial GIS products, including the CAPS Logistics Toolkit.

Revco Drugstores, Inc. implemented our ideas on self-balancing logistics systems on one of their pick lines at their central warehouse in Knoxville, TN. They have subsequently observed a 34% increase in pick rates. They now plan to extend the implementation to all the lines of the warehouse, and subsequently to additional warehouses.

Our contact in this has been Victor Lee, Director of Distribution Services of Revco Drugstores, Inc. In addition, we have met with the following, all of whom have expressed interest in trying out our ideas.

Sam Scozzaro  
Director of Distribution Services and Warehouse Operations  
Big B Drugstores

Nevin St. Romain  
Director of Distribution  
Blockbuster Music

Joel Page  
Operations Supervisor  
Eckerd Distribution Center

We are currently looking for a DoD warehouse that could profit from our ideas.

## **8. New discoveries, inventions, or patent disclosures**

(None)

## **9. Honors/Awards**

J. Bartholdi: Presidential Young Investigator Award, 1984--89